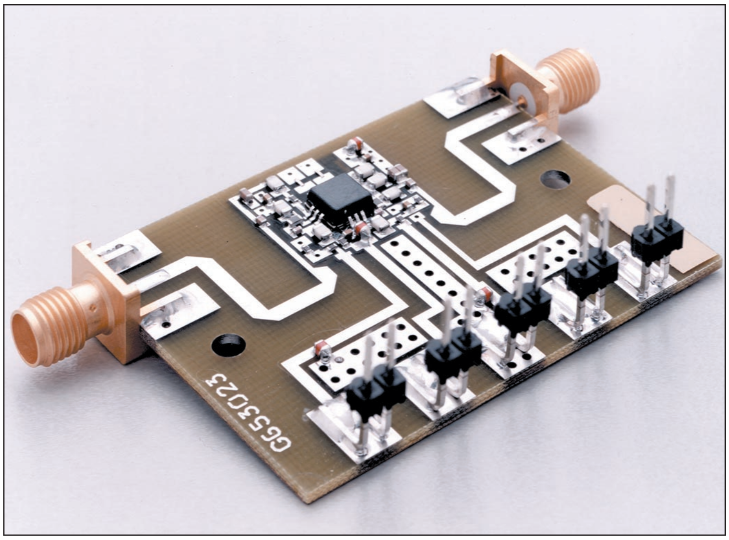
pHEMT MMIC Power Amplifiers for Base Stations and Adaptive Arrays

GaAs technology is used in a family of amplifiers for wireless applications requiring good gain, efficiency and linearity

Raymond S. Pengelly, Robert B. Binder, James R. Griffiths, Michael Virostko and Michael McPartlin
Raytheon Microelectronics

MMICs based on pseudomorphic HEMTs (pHEMTs) have been in volume production at Raytheon Microelectronics for several years. Applications include low-noise and power amplifiers from UHF through millimeter-wave. The largest single application for pHEMT technology is in power amplifiers for cellular and personal communication system mobile handsets. These power amplifiers presently operate in the voltage ranges of 3 to 7.5 volts depending on the generation of the platform. CDMA and TDMA phones require linear amplifiers where the maximum operating output power is typically backed-off 3 dB from saturated output power. Analog and GSM phones normally operate with power amplifiers that are much closer to their saturated output powers. The pHEMTs used in these designs have gate-to-drain breakdown voltages ranging from 14 to greater than 20 volts depending on the materials and gate-recess technologies used in their fabrication. A good rule-of-thumb for power amplifiers being driven to saturation is that the breakdown voltage should be 3 times the nominal operating voltage, e.g. a 4.8 volt PA requires a minimum breakdown voltage of 14.4 volts.



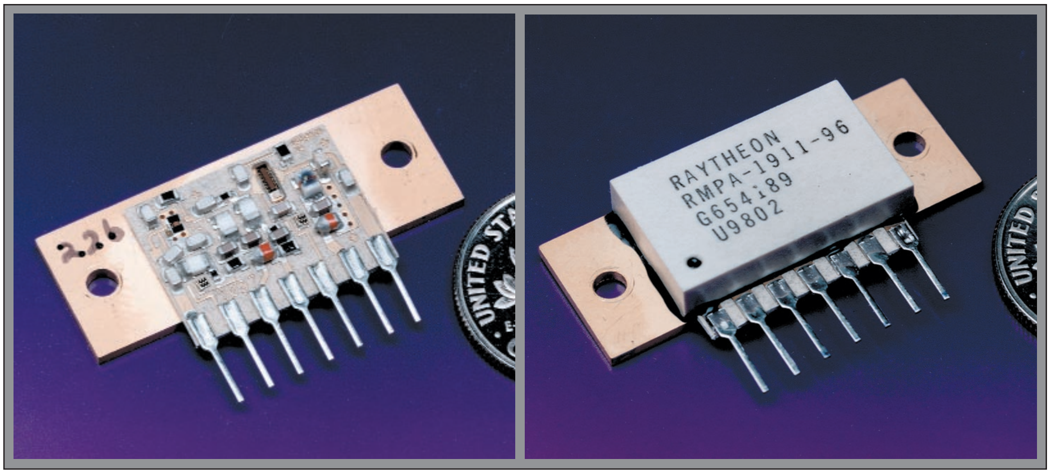
▲ **Figure 1. This pHEMT amplifier is shown in the PMBG-12 air cavity plastic metal base package.**

pHEMT power amplifiers operating in the cellular and PCS bands for reverse link applications (handset to base station) show excellent linearities and power added efficiencies (PAE), typically >65 percent PAE for saturated power and 40 percent for linear power (e.g. CDMA). Power amplifiers designed for forward link, multi-carrier (base station to handset) applications are normally operated with their output stages operating close to Class A. Efficiencies are in the 15 to 30 percent range for such amplifiers because of the much higher linearity and IMD requirements that require further power output back-off. For example, forward link CDMA uses QPSK modulation whereas reverse link uses OQPSK with a 6 dB higher peak-to-average power ratio in the former case. All the results in this article are for amplifiers that are unconditionally stable over specified source and load impedances and temperature ranges.

Output power as a function of operating voltage

The output power of a power amplifier is directly related to the square of the operating

voltage. Thus, an amplifier such as the RMPA1902-53, designed for 29 dBm linear output power under 1900 MHz CDMA operation at 3.5 volt should have a linear output power of greater than 34 dBm at 6.5 volts if the power output is not limited by incorrect output stage load impedances. Measurements confirm this relationship to be true. For linear operation where the amplifier will be typically backed off by between 3 and 6 dB the breakdown voltage of the transistors needs to be typically 2 times the operating voltage plus gate voltage, e.g. an 8 volt PA requires a minimum breakdown voltage of 16 + 1 = 17 volts.



▲ **Figure 2. The RMPA1911-96 35 dBm power amplifier is shown with the cover off (left) and in packaged form (right).**

Thermal considerations

It is important to consider the impact of total thermal resistance between the top surface of the GaAs die and the heat sink for power amplifier MMICs that were originally designed to operate at lower voltages. For example, the RMPA1902-53 amplifier was designed to operate nominally at 3.5 volts with a dissipated power of 1.5 watts at its full RF output power of 29 dBm. The GaAs die is silver epoxied into the PMBG-12 air-cavity plastic package with a measured thermal resistance of 17 deg C/watt. The PMBG-12 package (Figure 1) has a copper base for heat sinking.

The channel temperature rise above the package base temperature is about 25° C for that dissipated power. For a maximum operating temperature of 90° C the pHEMT channel is running at 115° C, well below the 150° C normally considered "safe" for long lifetime (i.e. at least 10 years). At 6.5 volts operating voltage the RMBA19500-53 (a derivative of the RMPA1902-53 using an additional heat-spreader between the GaAs die and the package metal base) has a dissipated power of 4.7 watts when delivering 2 watts linear RF power. The thermal resistance of this approach is 9° C/watt. For a PMBG-12 packaged MMIC soldered to the top surface of a PCB, whereby multiple via holes are used for thermal sinking as well as RF grounding, the channel temperature at a 90° C baseplate temperature is calculated to be 168° C. [90 + (4.7 × 9) + 36 (temperature rise through board)]. Mounting the packaged amplifier directly to a metal heat sink through the PCB results in a transistor channel temperature of <135° C at a 90° C heat-sink temperature. This is, therefore, the recommended mounting approach.

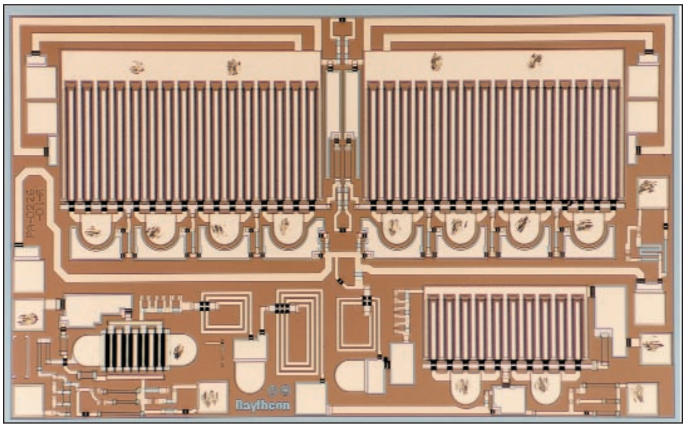
Typical pHEMT MMIC amplifier realization — Amplifier electrical design

Discrete and MMIC pHEMT amplifiers have been designed at Raytheon Microelectronics both for handset and base-station applications.

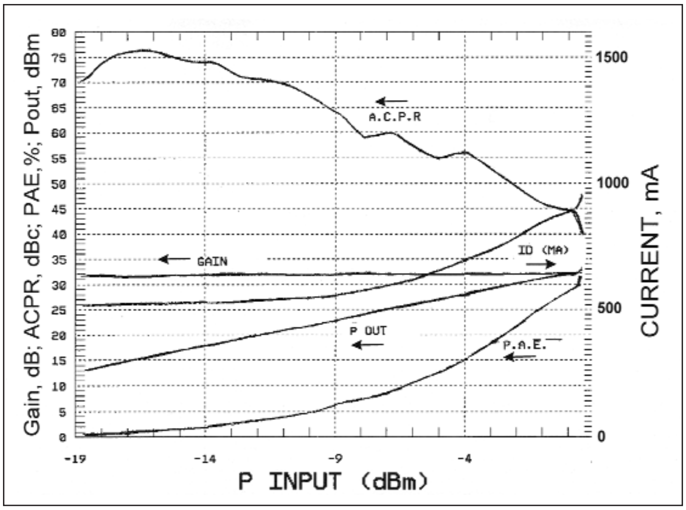
Figure 2 shows a photograph of a two-stage 35 dBm amplifier (RMPA1911-96) operating in the US PCS band This chip-on-board design using discrete pHEMTs has 27 dB gain and 30 percent PAE (under CDMA forward link operation) operating from an 8 volt rail. This amplifier has been used as a "building block" for higher power amplifiers as described later in this article.

Figure 3 shows a photograph of the MMIC used in a three-stage 33 dBm amplifier operating in the U.S. PCS band (RMBA19500-53). This air-cavity plastic packaged MMIC design has 30 dB gain and 30 percent PAE (under CDMA forward link operation) operating from a 6 volt rail. Again, this amplifier has been used as a "building block" for higher power amplifiers as described later in this article.

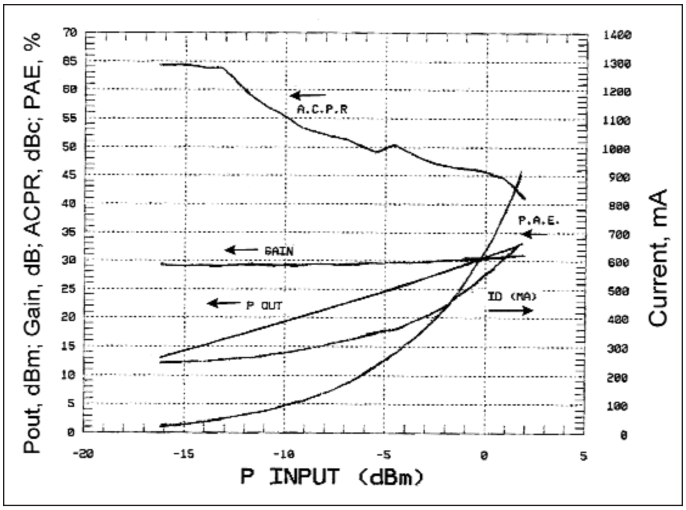
The design of these power amplifiers is primarily aimed at minimizing nonlinear effects and maximizing



▲ **Figure 3. 33 dBm linear power amplifier MMIC.**



▲ **Figure 4. Performance parameters of RMBA19500-53.**



▲ **Figure 5. Performance parameters of RMBA09500-53.**

efficiencies over different operating conditions determined by the system into which the amplifier is placed. An extreme example of this is that the biasing and load-line conditions for a "super-linear" amplifier requiring <–60 dBc IMD products will be different than the conditions required for an amplifier used in a TDMA application (Class A bias in the former case and Class A/B bias in the latter case). Generally, however, the design approaches follow similar paths. The main sources of spectral regrowth in pHEMT amplifiers are AM to AM distortion resulting from nonlinear transconductance, AM to PM distortion resulting from nonlinear gate-to-source capacitance, and distortion caused by waveform clipping at the gates and saturation and breakdown effects at the drains. The design issues that are addressed to minimize spectral regrowth are optimum fundamental frequency drain loading on all amplifier stages (but particularly the output stages), harmonic gate and drain loading and pre-distortion of the waveform through the amplifier. Pre-distortion is essential for linear operation as careful attention has to be paid to quiescent bias currents and transistor sizing to allow acceptable operation over temperature and maximization of power added efficiency.

Load-pull measurements of a range of transistor peripheries are required to determine the optimum pHEMT device sizes. The input and output of the transistors are tuned at specific bias currents. Contours of ACPR, output power, power gain, and PAE are plotted as a function of source and load conditions using automated systems such as ATN, Maury and Focus. Careful measurements result in the designer being able to choose a small impedance region where the chosen device has a "sweet spot" for best ACPR and PAE. Optimum efficiency is just as important in base station applications as in handset operation because significant reduction in "ancillary" equipment such as cooling fans and power supplies can result, making the amplifiers physically smaller and lower cost.

Base station driver amplifiers and phone PAs have critical requirements for stability. Stabilization techniques are required at the FET, MMIC, package and board levels. Peak performances (PAE, ACPR and Gain) are compromised when stabilization is added. Raytheon's amplifiers are tested into 10:1 load VSWRs over temperature with no RF as well as under small signal and compressed power levels.

Results under linear and nonlinear conditions

Figure 4 shows the P_{OUT} versus P_{IN} for the RMBA19500-53 operating under forward link CDMA conditions at 1900 MHz. Also shown is the PAE of the amplifier as well as the ACPR1 in dBc over a 19 dB dynamic range.

Figure 5 shows the P_{OUT} versus P_{IN} for the RMBA09500-53 operating under forward link CDMA conditions at 870 MHz. The PAE as well as the ACPR1 of the amplifier are shown over a 19 dB dynamic range.

These amplifiers provide 32 to 33 dBm of output power to the IS-95 forward link specification on ACPR. They are attractive as building blocks for driver and power amplifier applications as they are physically small (approximately 250 mil square package) and are competitively priced.

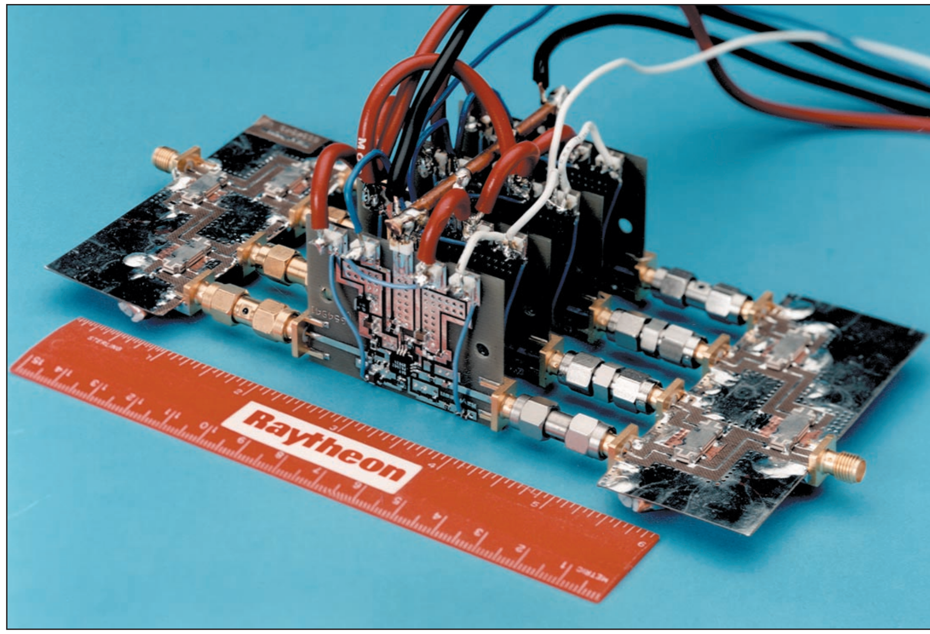
Differences between single carrier, multi-carrier, reverse link and forward link applications

There are two basic types of cellular systems – analog and digital. These systems require different types of base-station PAs.

Analog cellular systems include AMPS in the USA, ETACS/NMT in Europe and NTACS in Japan. Analog systems use Frequency Division Multiple Access (FDMA) and the power amplifiers that are required

operate in saturated mode with efficiencies as high as 60 to 70 percent. These power amplifiers must maintain harmonics below certain values depending on system requirements (e.g. –70 dBc). This perofrmance is achieved using harmonic terminations and filters.

Digital cellular systems include IS-54 TDMA in the USA which employs $\pi/4$ DQPSK modulation, GSM in Europe using GMSK and PDC in Japan using $\pi/4$ DQPSK modulation. In addition IS-95 CDMA has become popular in the USA, Hong Kong and Korea where OQPSK is used in the handsets and QPSK in the base-stations. Unlike GSM that employs constant envelope waveforms, the other digital standards have peak-to-average power envelope fluctuations that require linear power amplifiers to avoid spectral regrowth. This spectral regrowth may be defined by adjacent channel power ratio (ACPR) or an absolute spurious emission power level.



▲ **Figure 6. RMBA19520 power amplifier.**

ACPR = Adjacent Channel Power in dBm – Transmit Channel Power in dBm

For IS-54 and IS-136 TDMA operation: Channel Bandwidth = 24 kHz and Channel Spacing = 30 KHz. The spectral splatter is determined by the ACPR1 (Adjacent Channel) being ≤–30 dBc and the ACPR2 (Alternate Channel or next Adjacent Channel) being ≤–48 dBc.

For IS-95 and IS-98 the relevant linearity requirements are an ACPR1 of ≤–42 dBc at 885 kHz offset with a channel bandwidth of 1.23 MHz and an ACPR2 of ≤–54 dBc at 1.98 MHz offset.

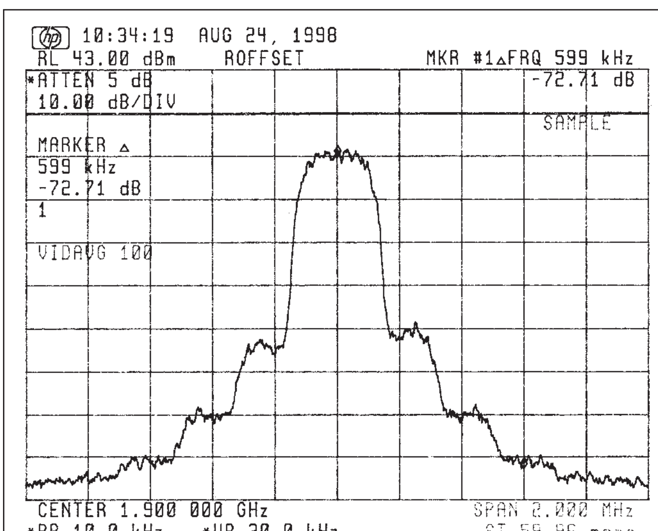
Base station splatter and emission level requirements resulting from multi-carrier transmissions result in more severe PA design requirements. In addition certain standards, such as CDMA, require more linearity in the base-station (forward link) PAs than in the handset (reverse link) PAs. In the CDMA case this is because the forward link modulation is QPSK with a 10 dB peak-to-average power envelope while the reverse link modulation is OQPSK with a 3 dB peak-to-average envelope.

Advantages of using pHEMT amplifiers in medium power linear applications

pHEMTs consistently show greater efficiencies than bipolar transistors and some MESFETs for highly linear applications e.g. 15 to 20 percent PAE compared to 5 percent under backed off power operation. pHEMTs, operating at voltages below 10 volts, are ideal for "low power" base-station and antenna array applications such as microcell, wireless local loop (WLL), "smart antennas" etc.. Such pHEMT amplifiers operating from 1 to >10 watts linear output power also find applications as driver amplifiers in macrocell sites.

Using pHEMT MMICs in higher power applications — Power combining

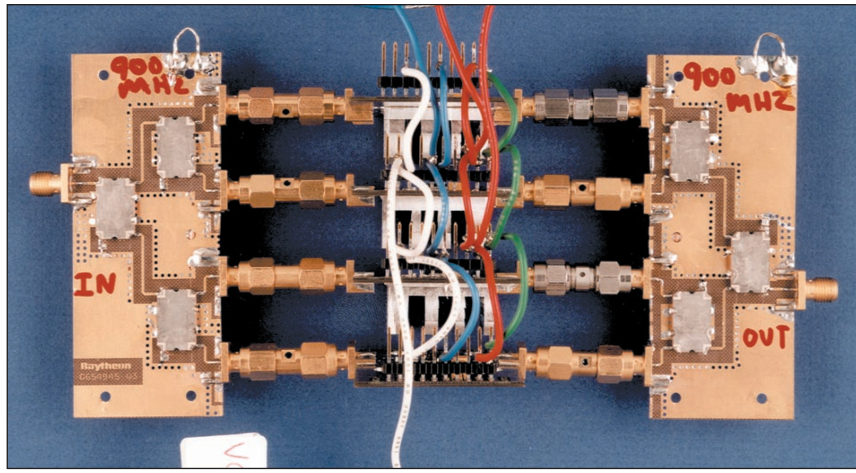
A number of discrete and MMIC-based amplifiers such as the RMBA09500-53, RMBA19500-53, RMPA1911-96 and RMPA2450-53 products have been used in higher power amplifiers by combining two, three and four units. All of these amplifiers have been



▲ **Figure 7. PHS emission level test at 5 watts output power.**

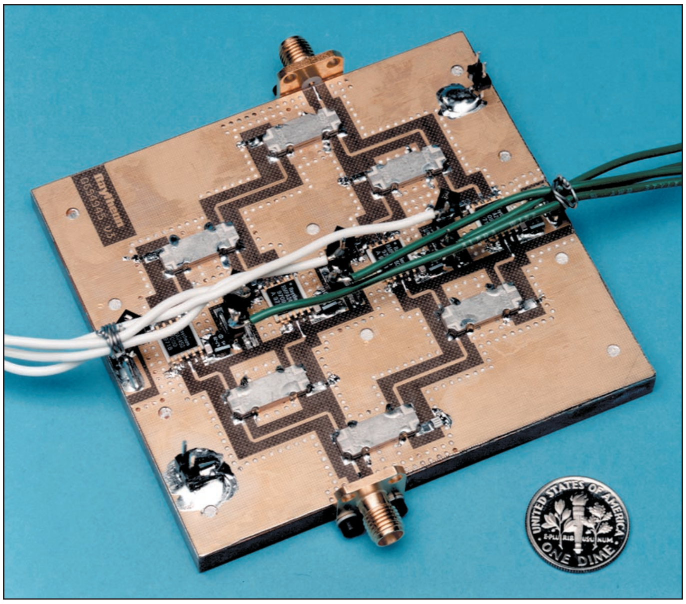
designed to operate from single drain and gate voltages (usually 6.5 or 8 volts on the drains and –3.5 volts on the gates).

Figure 6 shows the RMBA19520 consisting of four RMBA19500-53s operated at 6.5 volts. This amplifier has been used in a Japanese PHS rural microcell application, providing an output power of 5 watts, and an absolute emission level of 400 nanowatts at a 600 kHz offset (Figure 7). The same amplifier provides an output power of 6 watts under CDMA operation at an ACPR1 of 49 dBc under different biasing conditions. The overall PAE of the RMBA19520 is between 20 and 30 percent depending on mode of operation and biasing.

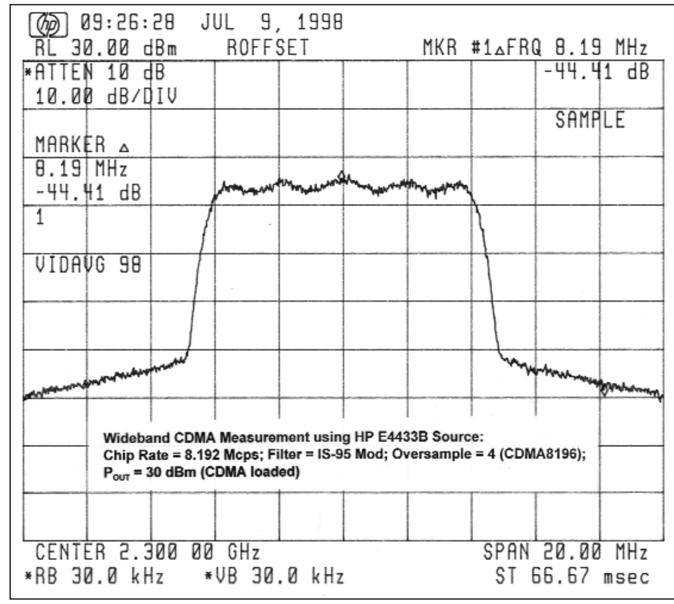


▲ **Figure 8. Photograph of the RMBA09520 cellular power amplifier.**

Figure 8 shows the RMBA09520 consisting of four RMBA09500-53s operated at 6.5 volts. This amplifier delivers 41.5 dBm saturated output power in Analog mode. For example the IMD of this amplifier is <–35 dBc at 10 watts output power at a PAE of 31 percent. Under digital modulation the amplifier delivers an output power of 38 dBm with a PAE of 29 percent with 45 dBc ACPR1 at 1.25 MHz offset for 1.23 Mbps forward link CDMA. The same amplifier, under different biasing conditions, provides 39 dBm output power at <–30 dBc ACPR1 and <–48 dBc ACPR2 at 30 and 60 kHz offsets for NADC TDMA with an overall PAE of 32 percent. Under GMSK modulation for 270



▲ **Figure 9. The RMBA23610 power amplifier.**



▲ **Figure 10. Wideband CDMA ACPR performance of the RMBA23610 at an output power of 1.25 watts.**

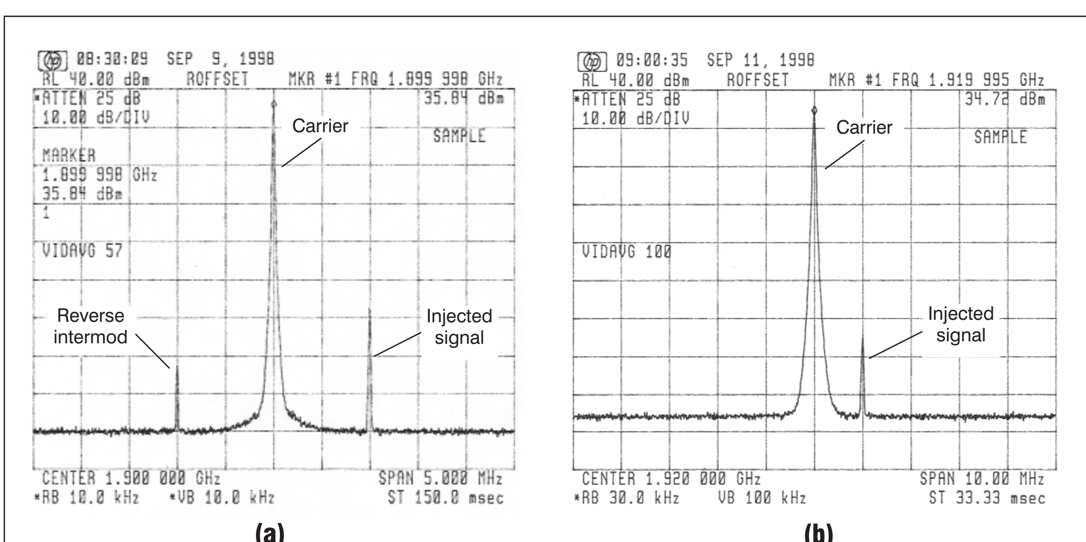
kbps the amplifier delivers 39 dBm output power at <–30 dBc and <–60 dBc emissions at 200 and 400 kHz offsets respectively.

Figure 9 shows a third power amplifier example using four RMPA2450-53 MMIC amplifiers. This amplifier is designed to be used under W-CDMA modulation at 8.2 Mcps for WLL applications at 2.3 MHz. The amplifier delivers 1.25 watts of linear power at an ACPR1 of –58 dBc. Figure 10 shows a wideband CDMA measurement using an HP E4433B digital modulation source. The four amplifiers are combined using Anaren Xinger surface mount couplers, are operated from 7 volts and have an overall PAE of 12 percent.

Table 1 and the accompanying notes provide a summary of various performance parameters for a number of pHEMT-based base-station power amplifiers available from Raytheon Microelectronics

Reverse intermodulation

One of the strictest emission level requirements in base-station system specifications is the so-called reverse intermodulation level. For example, for the 1900 MHz GSM requirement the reverse intermodulation level is an absolute power level at the power amplifier output of –70 dBm. In this case the reverse intermodulation product is defined as the resultant intermodulation signal produced when a + 4dBm single-tone signal is injected into the output of the power amplifier under full output power of 36 dBm. This measurement simulates the condition whereby a transmitter "receives" an adjacent channel signal from another nearby base-station. In order to prevent such signals being generated power amplifiers require "linear" isolators to be placed between the amplifier and the filters preceding the antenna. The lower the intrinsic



▲ **Figure 11. Reverse intermodulation: (a) without, and (b) with output isolator in a RMBA 19620 power amplifier.**

Part Number & Frequency	V_{DD} volts	P_{OUT} GSM dBm	P_{OUT} CDMA dBm	P_{OUT} TDMA dBm	P_{OUT} PHS dBm	P_{OUT} IMD dBm	Gain dB (S.S)	PAE % CDMA	P_{1dB} dBm CDMA	OIP_3 dBm CDMA	I/P & O/P VSWR	Noise Figure dB	Harmonics dBc (CW)
RMBA09500-53 840 to 900 MHz	6.5	34	31	34			30	30	34	44	2:1	5	- 30
RMBA09510 840 to 900 MHz	6.5	37	34	37			30	30	37	47	1.5:1	5.25	- 35
RMBA09520 840 to 900 MHz	6.5	39	38	40		40(b)	30	29	40	50	1.5:1	5.5	- 40
RMBA19500-53 1900 MHz	6.5		33	32	32		30	30	33.5	41	2:1	6	- 30
RMBA19510 1900 MHz	6.5		35	34	34		30	26	38	46	1.5:1	6.5	- 35
RMBA19520 1900 MHz	6.5		37	37	37	38(a) 27(b)	29	19	40	48	1.5:1	7	- 40
RMPA1911-96 1900 MHz	8		33	34		34(a) 21(b)	27	27	34	44	2:1	5	- 30
RMBA19600 1900 MHz	8					22(b)	27	24	35	45	2:1	6	- 30
RMBA19610 1900 MHz	8		35	36	34	36(a) 23(b)	27	11	36	45	1.5:1	5.5	- 35
RMBA19620 1900 MHz	8		36	37	37	37(a) 24(b)	26	14	39	48	1.5:1	6	- 40
RMPA2450-53 2300 MHz	7		25					12	27	37	2:1	5.5	- 30
RMPA2311-96 2300 MHz	8		30					12	32	42	2:1	5.5	- 30
RMBA23610 2300 MHz	7		31				30	12	33	43	1.5:1	6	- 40

Notes

1. The linearity parameters are not necessarily available simultaneously. The amplifiers are biased for optimum performance for each type of modulation scheme or linearity requirement. POUT is linear output power to meet one or more of the following specifications:
GSM: 270.8 kHz symbol rate; Forward Link; GMSK modulation; @ 200 kHz offset ACPR1 = 35 dBc; @ 400 KHz offset ACPR2 = 65 dBc
CDMA: 1.23 MHz symbol rate; Forward Link; 9 Channels
@ 1.23 MHz offset in 30 kHz integration bandwidth ACPR1 = 46 dBc; @ 2.5 MHz offset in 30 kHz integration bandwidth ACPR2 = 64 dBc
TDMA: NADC with 48.6 kHz symbol rate; @ 30 kHz offset ACPR1 = 30 dBc; @ 60 kHz offset ACPR2 = 48 dBc
PHS: Relative emission level of –70 dBc at Bit Rate of 384 kbps at offset frequency of 600 kHz
IMD: (a) Third Order Two Tone Rejection >30 dBc; (b) Third Order Two Tone Rejection >60 dBc; This parameter does not refer to reverse IMD
2. Baseplate Operating Temperature Range: 0° C to +50° C. These amplifiers do not contain temperature compensation unless specified by the customer. Gain change with temperature is approximately 0.02 dB per °C
3. Non-operating Temperature: -40° C to + 85° C; Humidity without condensation: 95% relative; Altitude: 10,000 feet
4. Outlines are to customer requirements; normally consist of either machined enclosures with gasket seals, SMA Female or Type N Female connectors, EMI/RF filters or tab leaded modules
5. Single Power Supply. Maximum supply without damage: 10 volts
6. Load Mismatch sustainable without damage: 3.0:1

Packages

Type 53 is a 12 lead "quad" plastic package with metal base; Type 96 is a 7 "edge" leaded package with flange.

▲ **Table 1. Summary of performance parameters of pHEMT-based base station power amplifiers.**

Temp. Deg. C	Small Signal Gain, dB	Large Signal Gain, dB	Quiescent Current, mA	RF Loaded Current, mA	ACPR1, dBc
-38	26	25.9	1800	2500	46.2
-30	26	25.7	1730	2520	45.6
-20	25.9	25.6	1660	2560	45.1
-10	25.6	25.4	1570	2630	46.5
0	25.4	25.1	1580	2700	45.1
10	25.1	24.8	1430	2773	46.6
20	24.9	24.7	1410	2780	45.0
30	24.7	24.4	1410	2850	45.0
40	24.7	24.2	1370	2900	45.0
50	24.4	24.0	1360	2950	44.0
60	24.2	23.8	1290	3000	44.5
70	24.0	23.5	1330	3070	44.3
80	23.5	23.2	1340	3130	44.2

▲ **Table 2. Variation in performance of the RMBA 19620 as a function of temperature.**

reverse intermodulation of the power amplifier the less stringent the requirements placed on the “linear” isolators (isolators chosen specifically to exhibit very small nonlinear effects). Figure 11 shows the reverse intermodulation of the RMPA19620 that results from using a standard isolator compared to no isolator. With the isolator connected the reverse intermodulation level is <–115 dBc (or –79 dBm) compared to –96 dBc (or –60 dBm) without the isolator.

Typical amplifier performance versus temperature

The amplifiers described above do not feature temperature compensation. In many cases temperature compensation is not required because the intrinsic variation in gain etc. of the amplifiers using pHEMTs is acceptably small. Table 2 shows the typical parameters of the RMBA19620 1900 MHz amplifier as a function of temperature. The ACPR1 figures refer to 9 channel forward link CDMA conditions with QPSK modulation. The measurements were performed by setting the output power to 36 dBm by adjusting input RF power at each temperature and recording the parameters that are tabulated. The amplifier quiescent current was set to a nominal value at 20° C only. The measured temperature coefficient of gain over –38° to + 80° C. is 0.02 dB per °C.

Conclusions

pHEMT transistors have been used effectively in a range of power amplifiers for cellular and PCS base-station applications. These amplifiers, having linear output powers in the range of 1 to 10 watts, show excellent efficiencies when compared to BJT and MESFET based products.

Low operating voltages coupled with relatively high efficiencies result in simplified construction and installation of the amplifiers. This makes them suitable for masthead applications where convection cooling is sufficient to maintain the amplifiers below safe operating temperatures. A number of examples of such amplifiers have been described in this article together with typical data for a range of constant envelope and linear modulation conditions. ■

Author information

Raymond S. Pengelly, Robert B. Binder, James R. Griffiths, Michael Virostko, Michael McPartlin are with Raytheon Microelectronics, 362 Lowell Street, Andover, MA 01810. They can be reached by telephone at: 978-470-9715, by fax at: 978-470-9452, or by e-mail at: Raymond_S_Pengelly@me.raytheon.com. Further information can be obtained from the Raytheon Web site: www.raytheon.com/micro.